MEMORANDUM REPORT ARBRL-MR-03366

PROPELLANT GAS FLOW DURING SHOT EJECTION

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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For lower projectile velocities, a rarefaction wave moves into the bore from the muzzle after shot ejection. Acoustic thermometry, used to determine the temperature of the propellant gases near the muzzle, assumes that the rarefaction wave is one-dimensional. In the present report, a numerical simulation is used to compute the wave motion within the gun immediately following shot ejection. The results describe the initial development of the flow; within the gun tube the rarefaction wave becomes one-dimensional quickly enough for the assumption from acoustic thermometry to be a good approximation.

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I. INTRODUCTION

The properties of the propellant gas near the muzzle during and shortly after shot ejection are of interest since they determine the magnitude of the muzzle blast overpressure. One important property is the temperature. Schmidt, Gion, and Shear[1] designed an apparatus to measure the sound speed and thereby calculate a temperature by assuming an equation-of-state for the propellant gas. Schmidt, et al[1] measured the propellant gas pressures as a function of time at different locations near the muzzle. For slower moving projectiles, the propellant gas behind the projectile has subsonic flow conditions immediately before shot ejection. After the projectile uncorks from the muzzle, an expansion wave propagates into the gun tube. They approximate this expansion wave as being one-dimensional and thereby deduce the sound speed. Further approximations may be made to calculate the propellant temperature.

The complexity of the starting expansion wave might contribute toward the disagreement in temperature between experimental results and predictions from interior ballistics theory.[2-5] Immediately after shot ejection, the expansion wave entering the gun tube is two-dimensional. Gough[2] contends that the initial two-dimensional nature of this wave might mask any effects produced by the initial chemically frozen wave propagating into the tube. He also concludes that "The geometrical dispersion due to the two-dimensional geometry of the unloading wave is too complicated to quantify as a source of error without further study." With the NOVA simulation code, Gough also found that the temperature of the propellant gas near the base of the projectile was markedly higher. Additionally, Celmins[3] indicates that the usual assumption of a very slow variation in propellant gas temperature with distance from the muzzle might not be valid.

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1. *E. M. Schmidt, E. J. Gion, and D. D. Shear, "Acoustic Thermometric Measurements of Propellant Gas Temperatures in Guns," U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, BRL Report BRL-R-1919, August 1976 (AD A030359)*

2. *P. S. Gough, "On the Determination of the Gas Temperature from the Velocity of the Muzzle Rarefaction Wave," U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, BRL Contractor Report BRL-CR-00504, February 1983 (AD A125479).*

3. *A. Celmins, "Theoretical Accuracy of Acoustic Gas Temperature Measurements in Guns," U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, BRL Technical Report ARBRL-TR-02134, January 1979 (AD A068461).*

4. *A. Celmins, "Theoretical Basis of the Recoilless Rifle Interior Ballistics Code RECRIF," U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, BRL Report BRL-R-1931, September 1976 (AD B013832L).*

5. *P. G. Baer and J. M. Frankle, "The Simulation of Interior Ballistic Performance of Guns by Digital Computer Program," U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, BRL Report BRL-R-1183, 1962 (AD 299980).*

It is the objective of this work to examine the one-dimensional assumption and the flow details near the muzzle after shot ejection. The time for transition from two-dimensional to one-dimensional flow is ascertained and the effects upon the acoustic thermometry measurements and flow exterior to the gun barrel muzzle is discussed. A gun-blast numerical-simulation code[6,7] modified for the particular problem is used to calculate the flow properties both inside and outside the gun barrel. The results of the simulation can be compared with an experiment conducted at BRL.[8] To examine the transition from a two-dimensional flow to the one-dimensional rarefaction wave, Mach contours are used to describe the different stages of the gun exhaust cycle.

II. EXPERIMENT

In acoustic thermometry, the velocity of propagation of an acoustic wave is found by measuring the time for it to travel a known distance. For this experiment, the disturbance is generated when the projectile uncorks and an expansion wave travels into the bore at a velocity equal to the propellant gas speed of sound minus the local outflow velocity of the propellant gases. An in-bore wave diagram is shown in Figure 1. Five pressure transducers, mounted flush in the tube wall near the muzzle, record the passage of the expansion wave. A pressure-time curve generated by the experiment is shown in Figure 2. The rise in the first part of the pressure curve is caused by air being compressed ahead of the projectile as it travels down the tube. The rapid rise in pressure is associated with the passage of the projectile over the pressure transducer. There is then a decay caused by in-bore waves reflecting from the breech and the base of the projectile. After the projectile clears the muzzle, the expansion wave travels back toward the transducer and, as it passes, the recorded pressure declines at a faster rate. The velocity of the propellant gases before the expansion reaches the transducers is assumed to be the projectile exit velocity; with the distances between transducers known and rarefaction wave time of arrival observed, the propellant speed of sound can be deduced. With an equation-of-state for the propellant gas assumed, the propellant gas temperature can be estimated.

For this particular experiment, a square-based plastic projectile with a reduced loading of propellant is used in a 30 mm WECOM cannon with the muzzle device attached as shown in Figure 3. Five pressure transducers were used in the muzzle device. The distances of the gages from the muzzle are given in Table 1.

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6. *G. F. Widhopf, J. C. Buell, and E. M. Schmidt, "Time-Dependent Near Field Muzzle Brake Flow Simulations," AIAA Paper 82-00973, AIAA, New York, NY, June 1982.*

7. *J. Huizinga, G. Grunwald, and N. French, "Mobile ICBM Transporter Launcher Blast Loading and Hardness Assessment," Lockheed Missiles and Space Company Report LMSC-D053108, Huntsville, AL, December 1970.*

8. *K. S. Fansler and G. E. Keller, "Variation of Free-Field Muzzle Blast with Propellant Type," 6th International Symposium on Ballistics, Orlando, FL, October 1981, ADPA, Arlington, VA.*

TABLE 1. GAGE DISTANCES

Gage Number	Distance from Muzzle (mm)
1	7.0
2	19.7
3	32.3
4	45.1
5	57.7

The M10 propellant charge was designed to burn up well before the projectile exits the gun tube to minimize two-phase gas effects. The parameters of the experiment are given below in Table 2.

TABLE 2. WEAPON PARAMETERS

Bore diameter, D	30 mm
Bore and chamber volume, U	760 cm^3
Projectile mass, M_p	112.9 gms
Projectile velocity, V_p	572 m/s
Propellant mass, C	12.96 gms
Specific heat ratio, γ	1.234
Flame temperature, T_a	3000.°K
Specific force, F	$1.014*10^6$ $(m/s)^2$

III. NUMERICAL MODEL

The inviscid model for gun blast developed by Widhopf, et al [6] is used. With this model, a conservative form of the unsteady Euler equations is solved using a one-component compressible gas. These equations are:

$$(\rho y)_t + (\rho v y)_y + (\rho u y)_x = 0 \tag{1}$$

$$(\rho u y)_t + [y(p + u^2)]_x + (\rho u v y)_y = 0 \tag{2}$$

$$(\rho v y)_t + (\rho u v y)_x + [y(p + v^2)]_y - p = 0 \tag{3}$$

$$(\rho e y)_t + [\rho u y(e + p/\rho)]_x + [\rho v y(e + p/\rho)]_y = 0 \tag{4}$$

$$p = (\gamma - 1)\ e \tag{5}$$

Here p is the pressure, x and y are the coordinates in the axial and radial directions respectively, u and v are the velocity components in the x and y directions respectively, ρ is the fluid density and e is the specific internal energy.

The simulation code utilizes Godunov's scheme.[9] The fluxes at the cell surfaces are determined by solving Reimann's problem. Updated conservation values are obtained using these obtained fluxes in the conservation equations with a first order time differencing. Surface properties are treated using analytic expression for one-dimensional wave reflections together with the boundary condition that the normal component of the velocity is zero.

This implementation of the Godunov method permits cells to be sized differently to optimize resolution of flow structure, decrease computational time and save core memory. Square cells with dimensions of 1 mm were placed throughout the bore from the muzzle to a position somewhat rearward of the last transducer placed in the gun barrel for the experiment. The cells in the regions away from the transducers are of less interest and are made larger. The simulation technique is also modified to allow the projectile base to be initially at the muzzle plane position. This modification allows a more detailed study of the formation of the expansion wave.

The initial conditions outside the gun bore are given as ambient. Although a precursor blast wave is generated by the projectile pushing air out of the gun barrel, this is neglected in the present calculations. The in-bore conditions are assumed to be Lagrangian;[10] that is, the velocity of the propellant gas increases linearly from the value zero at the breech to the projectile velocity at the base of the projectile. The propellant gas density is assumed constant and the pressure increases from the muzzle to the breech according to the equation,

$$p = p_m \{(1 - C/2m_p) [(L+x)^2/L^2]\} \tag{6}$$

where p_m is the pressure at the muzzle immediately before uncorking, L is the length of the barrel and x is the axial coordinate with x=0 corresponding to the muzzle plane. The muzzle pressure assumed for the problem is the value found by a simple internal ballistic theory. The muzzle pressure is 83 MPa; by knowing the propellant charge mass and the bore-chamber volume, the density at uncorking is calculated to be 170.5 kg/m.^{3} The ideal gas equation of state gives the pre-uncorking speed of sound at the muzzle, a, as 775 m/s.

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9. *S. K. Godunov, A. B. Zabrodin, and G. P. Prokopov, "A Computational Scheme for Two-Dimensional Nonstationary Problems of Gas Dynamics and Calculation of the Flow from a Shock Wave Approaching a Stationary State," U.S.S.R. Computational Mathematics and Math Physics, May 1961, pp. 1187-1219.*

10. *J. Corner, Theory of the Interior Ballistics of Guns, John Wiley, NY, 1950.*

IV. RESULTS AND COMPARISON WITH EXPERIMENT

Figure 4 shows a sequence of Mach contours generated by the numerical simulation technique. For clarity, Mach contours are displayed in a small range around the sonic line. The solid line closest to a dotted line is the sonic line. The contours above the projectile correspond to the recompression shock for the propellant gas plume. Initially, the wave front should advance downward between the projectile and the muzzle at a speed equal to a, while the wave front should travel rearward with the speed a-u. The contour shapes in the sequence seem to indicate that this is occurring. As the wave travels rearward, the contour lines straighten out rapidly. Utilizing the pre-uncorking speed of sound calculated in the previous section, the head of the wave should reach the first transducer between the 80th and the 90th steps. The contour lines at the position 7 mm from the muzzle are almost straight at these times. The sonic line is also approaching the muzzle plane by 90 cycles. Thus, essentially, a flow pattern is established in time to obtain data for a one-dimensional rarefaction wave sweeping over all transducers.

It is usually assumed that the mass flux issuing from the muzzle plane has sonic conditions when performing a muzzle blast simulation. This assumption saves computation time and core memory. Examining the contour sequence in Figure 4, the sonic line is seen to be near the muzzle plane by the 90th cycle of computation. At this time,the muzzle blast front is still quite close to the muzzle. Thus, it appears that the assumption is valid for muzzle blast simulations.

It is also of interest to compare the pressure-time curves obtained by the numerical simulation technique with the data obtained with the pressure transducers. Figure 5 shows the sequence of pressure-time curves at the various transducer positions obtained by both experiment and calculation. On the whole, the initial values for the pressure are slightly higher utilizing interior ballistic theory with full burn-up of the powder assumed. However, it is likely that the powder is not completely burnt. It is also noted that the pressure fall-off is more rapid for the experiment than for the simulated results. The major source of the disagreement is thought to be caused by the different sound speeds found for experiment and interior ballistics theory. The experimental value was found to be approximately 840 m/s whereas the interior ballistics value is 775 m/s assuming the ideal equation-of-state. Assumption of the more realistic Abel equation-of-state changes the calculated sound speed only an insignificant amount. Of course, faster sound speeds correspond to faster propellant gas emptying and therefore a faster pressure fall-off. Studies indicate[2,3] that the propellant gas near the base of the projectile could have a higher temperature than in the region toward the breech. The lack of better agreement may also be caused partially by the large artificial viscosity implicit in the first order Godunov technique. Implementation of second order Godunov schemes[11,12] might produce a crisper more definitive waveform and better agreement with experiment.

If the one-dimensional assumption is valid for the projectile in the flow field, one might expect that there ought to be good agreement between the results when the projectile was included and when the projectile was not included. Without the projectile, the flow field within the bore is essentially one-dimensional immediately after firing and remains so. Figure 6 shows a comparison between the pressure obtained with and without a projectile in the flow field. This sequence was run using slightly lower muzzle exit conditions than the former sequence. As might be expected, the pressures calculated at the transducer are at first identical. Later, the effect of obstruction at and near the muzzle is seen to cause the pressures to be slightly higher. Nevertheless, the general shape of the curve is unaltered and wave speeds deduced from the two cases would be expected to be nearly identical.

VI. CONCLUSIONS

For all practical acoustic thermometry experiments of interest, the one-dimensional assumption for the rarefaction wave appears valid. Comparison between simulation and experiment yields fair agreement. The major source of disagreement stems from the higher sound speeds obtained by experiment. The reason for the higher sound speeds is not known although there have been some explanations for this behavior.[3] Of course, if the numerical model were modified to take into account the possibility that higher temperatures were obtained near the muzzle, the results from the numerical model would much more closely approximate the experimental results. Most previous experimenters have obtained lower sound speeds, but some of the results could be attributed to incomplete burning.

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11. *Bram van Leer, "Towards the Ultimate Conservation Difference Scheme. V. A Second Order Sequel to Godunov's Method," J. Comp. Phys. (32), pp. 101-136, 1979.*

12. *S. Eidelman, P. Colella, and R. P. Shreeve, "Application of the Godunov Method and Higher Order Extensions of the Godunov Method to Cascade Flow Modeling," AIAA-83-1941-cp, AIAA 6th Computational Fluid Dynamics Conference, Danvers, MA, July 13-15, 1983.*

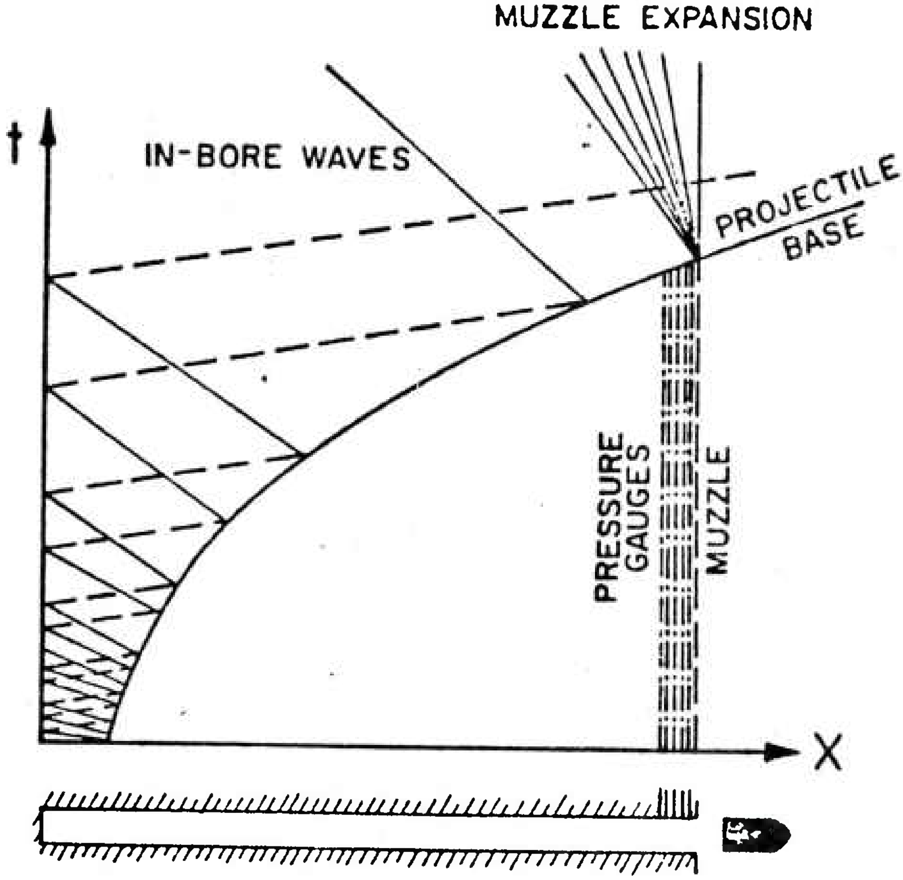


Figure 1. In-Bore Wave Diagram

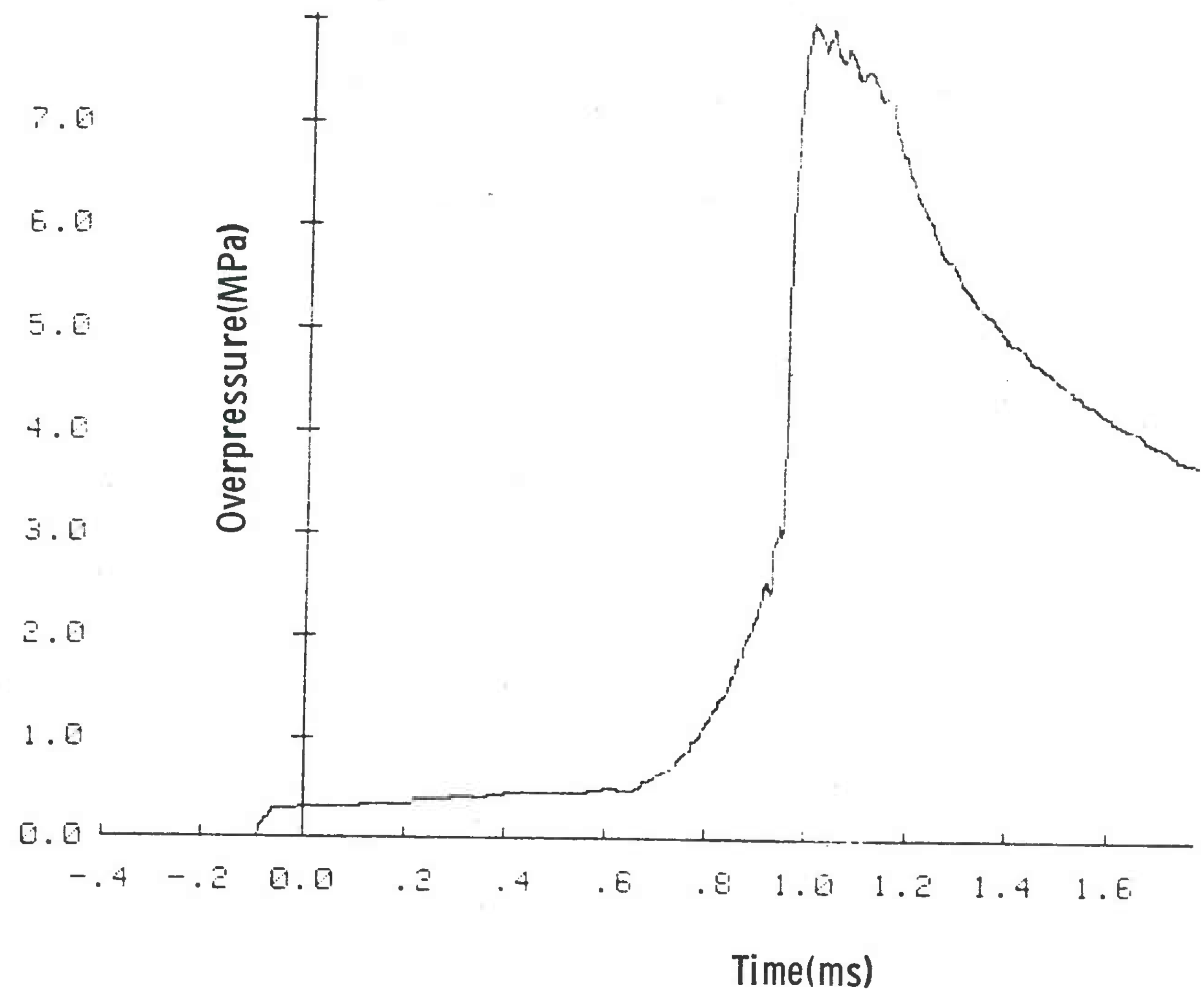


Figure 2. Pressure-Time Trace at Transducer Station

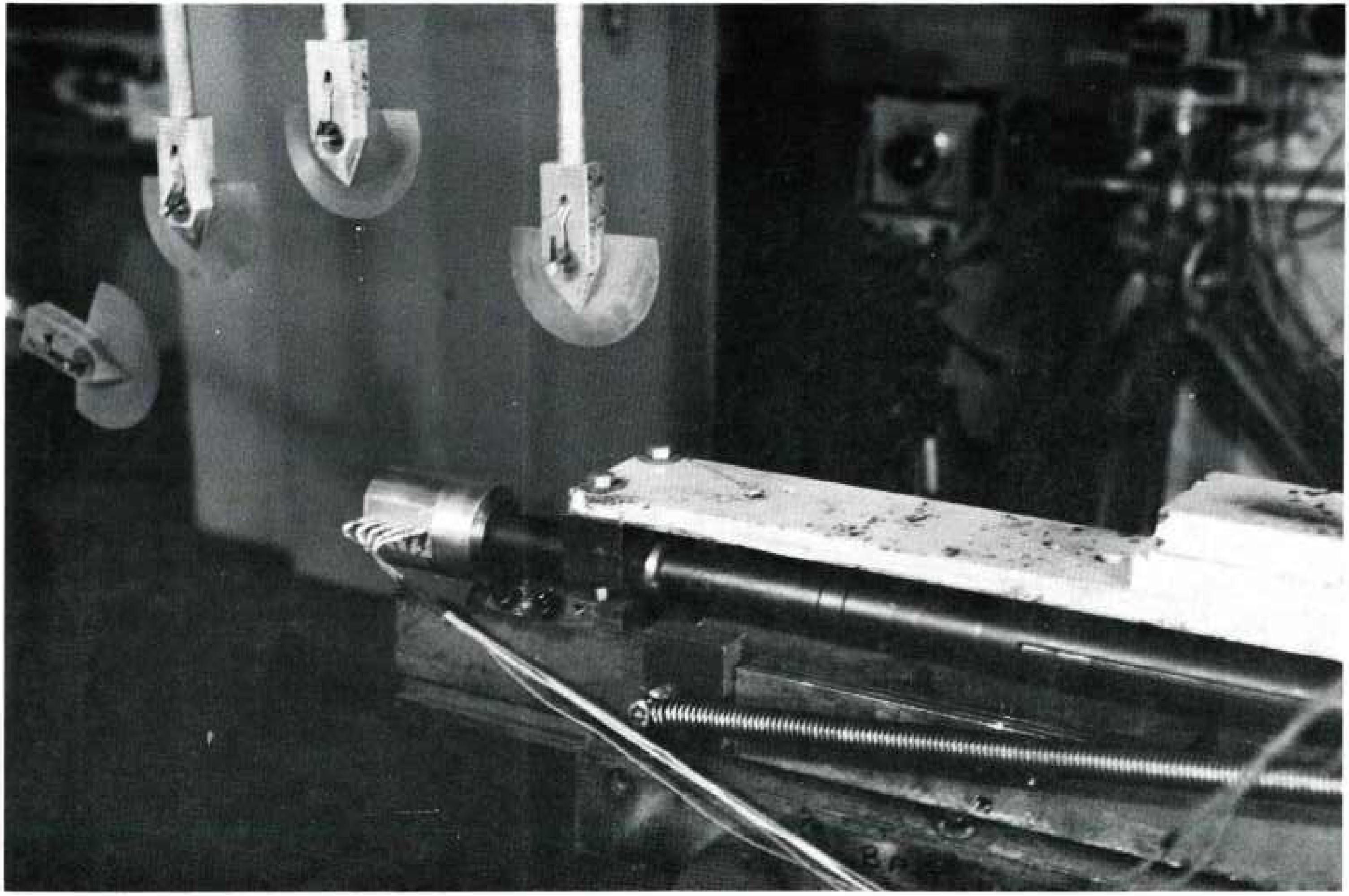
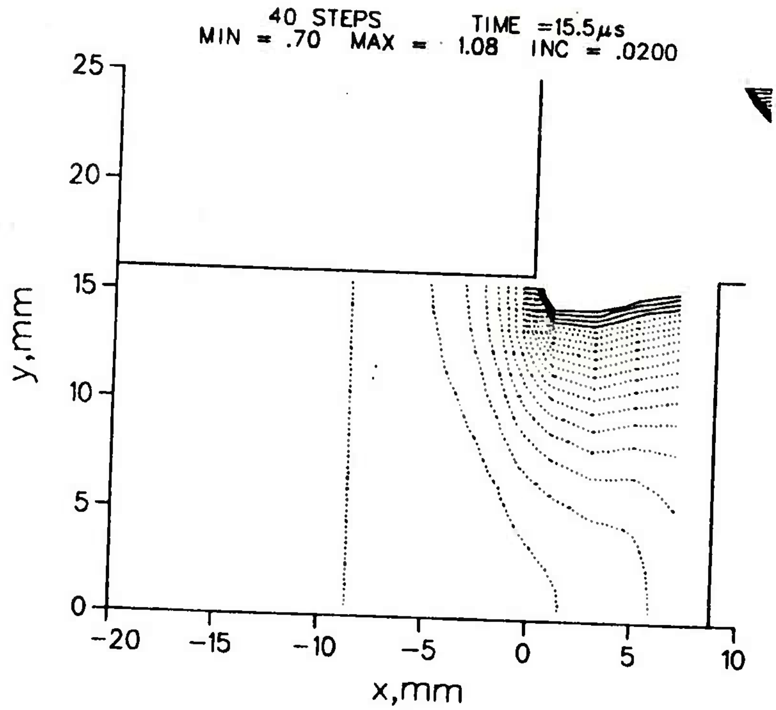


Figure 3. Experimental Setup



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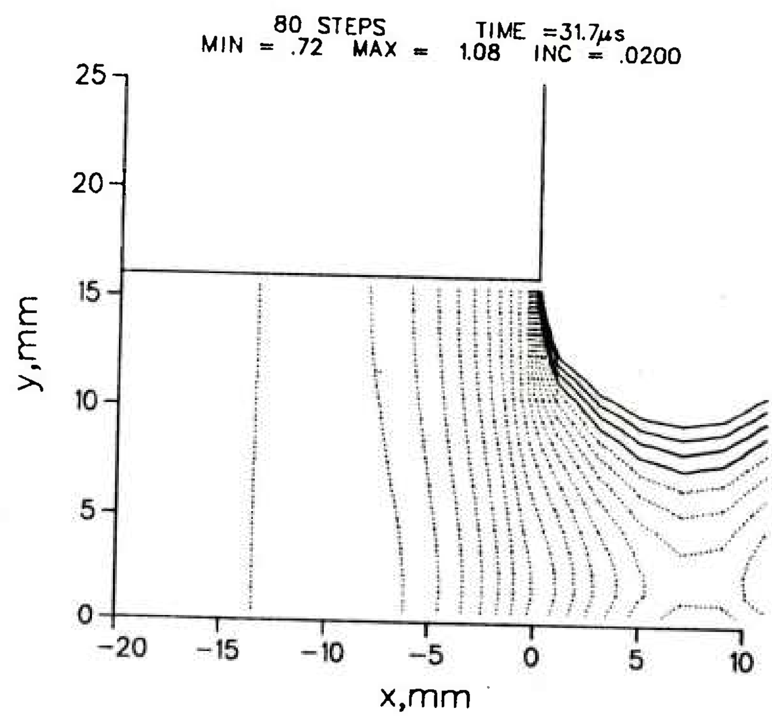
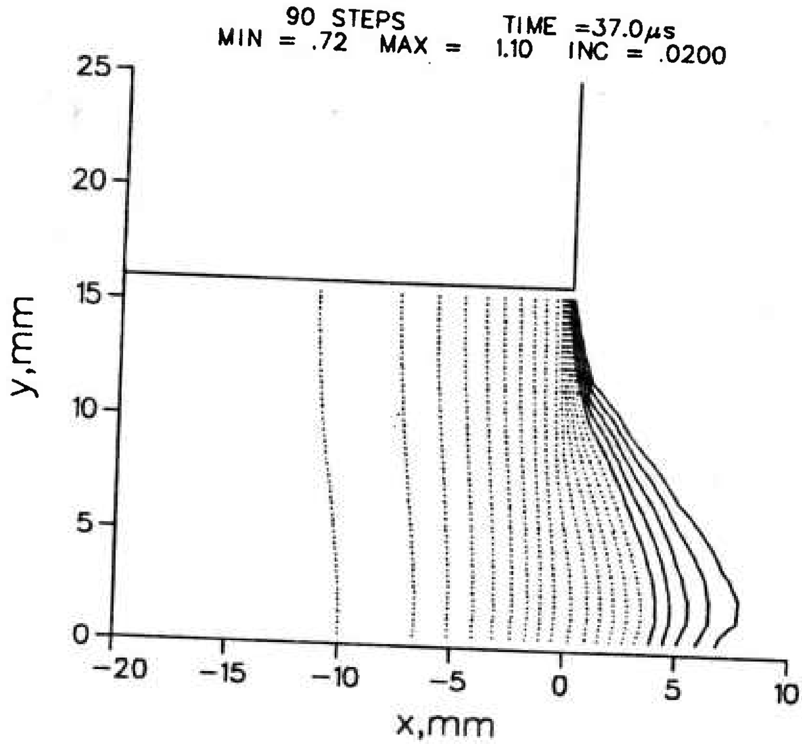


(b)

Figure 4. Mach Contours - In-Bore and Around Muzzle (continued)



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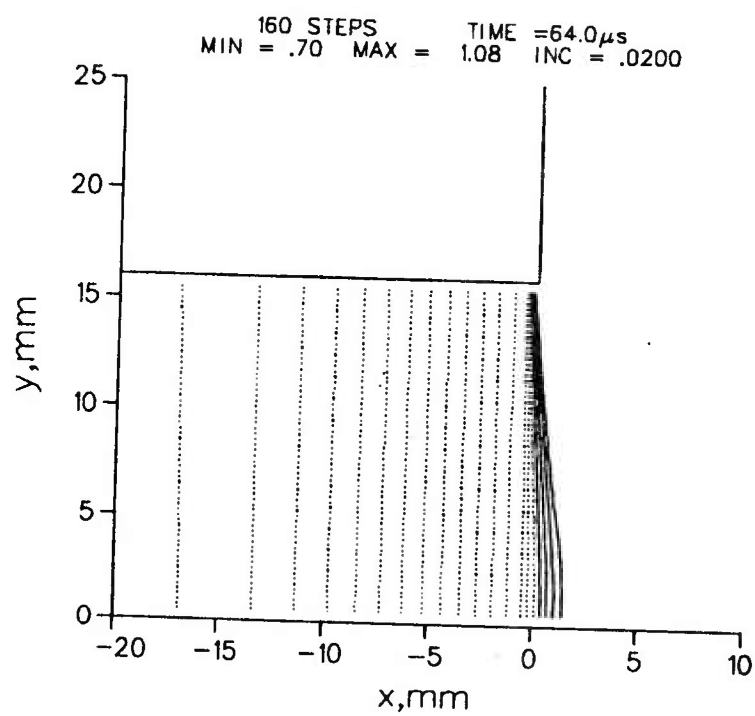
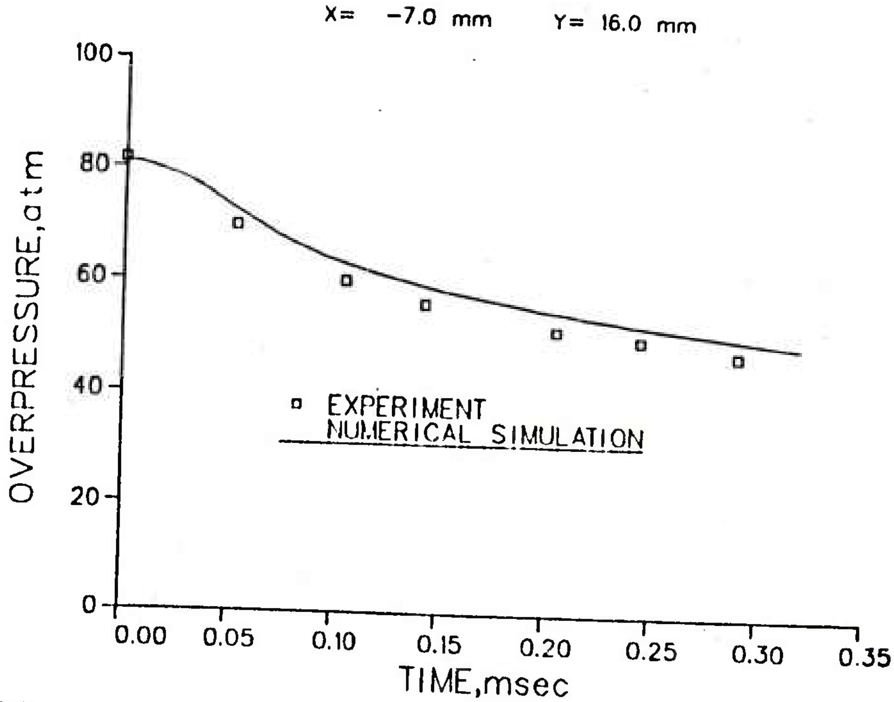


(d)

Figure 4. Mach Contours - In-Bore and Around Muzzle



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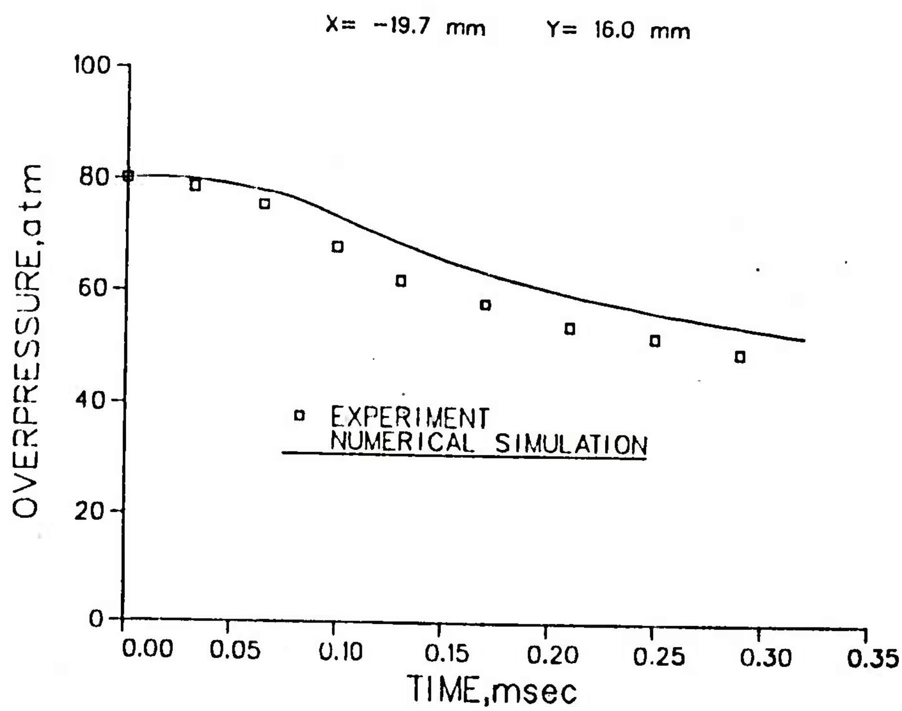
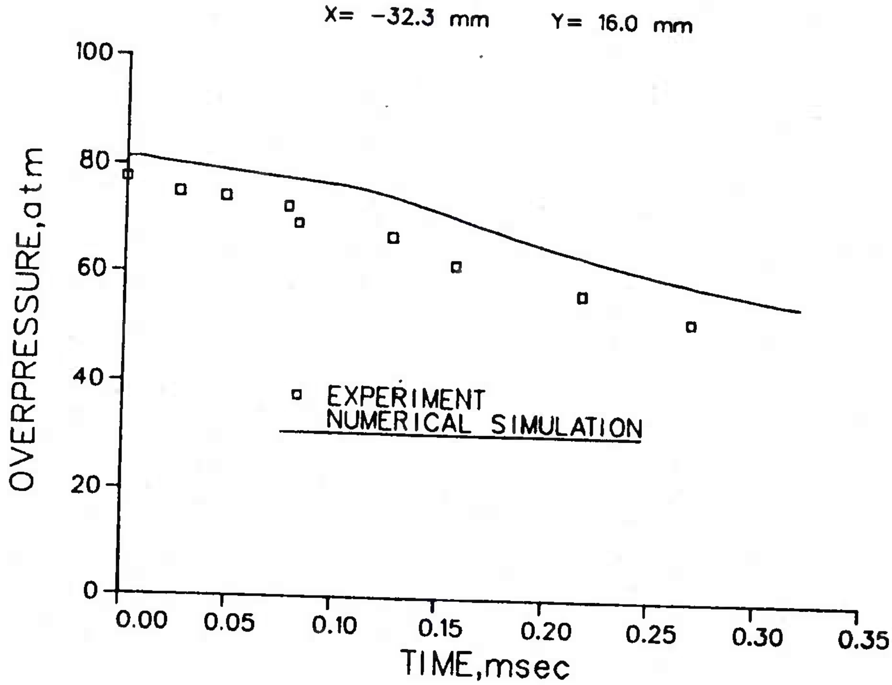


(b)

Figure 5. Pressure-Time Curves - Simulation vs Experiment (continued)



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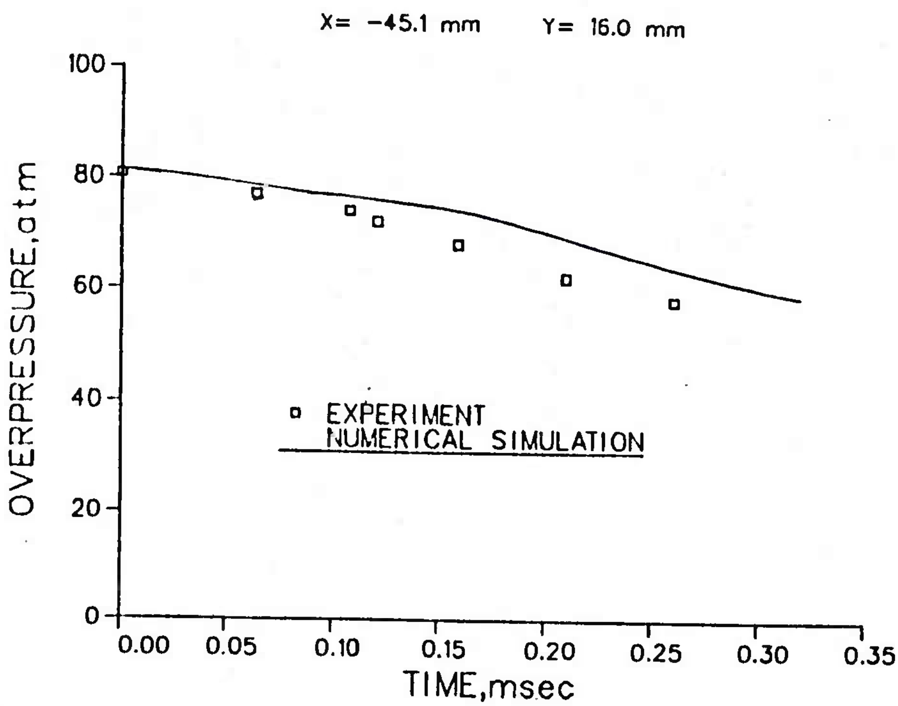

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Figure 5. Pressure-Time Curves - Simulation vs Experiment (continued)

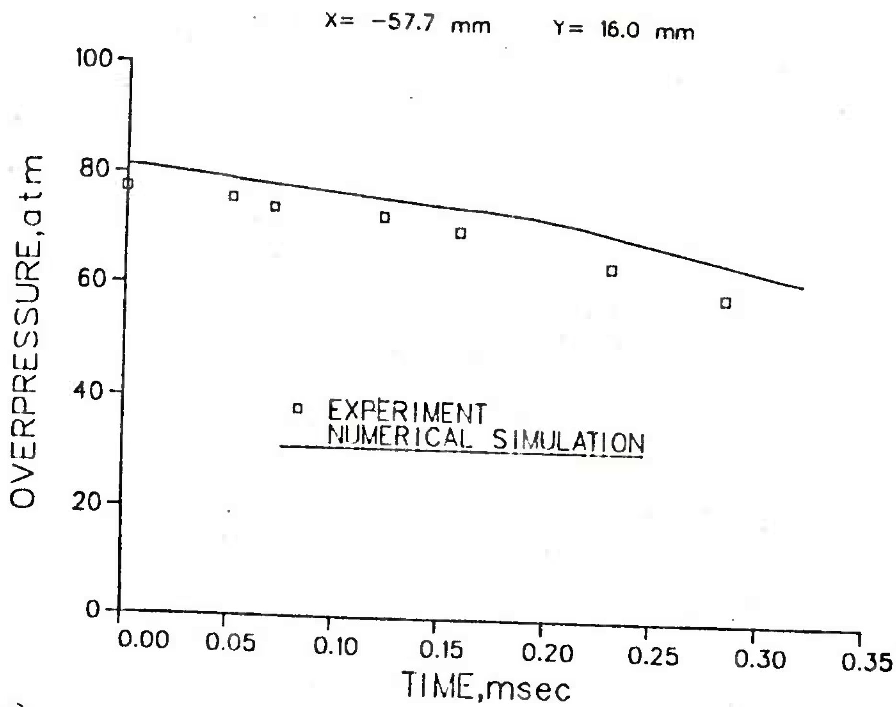

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Figure 5. Pressure-Time Curves - Simulation vs Experiment (continued)

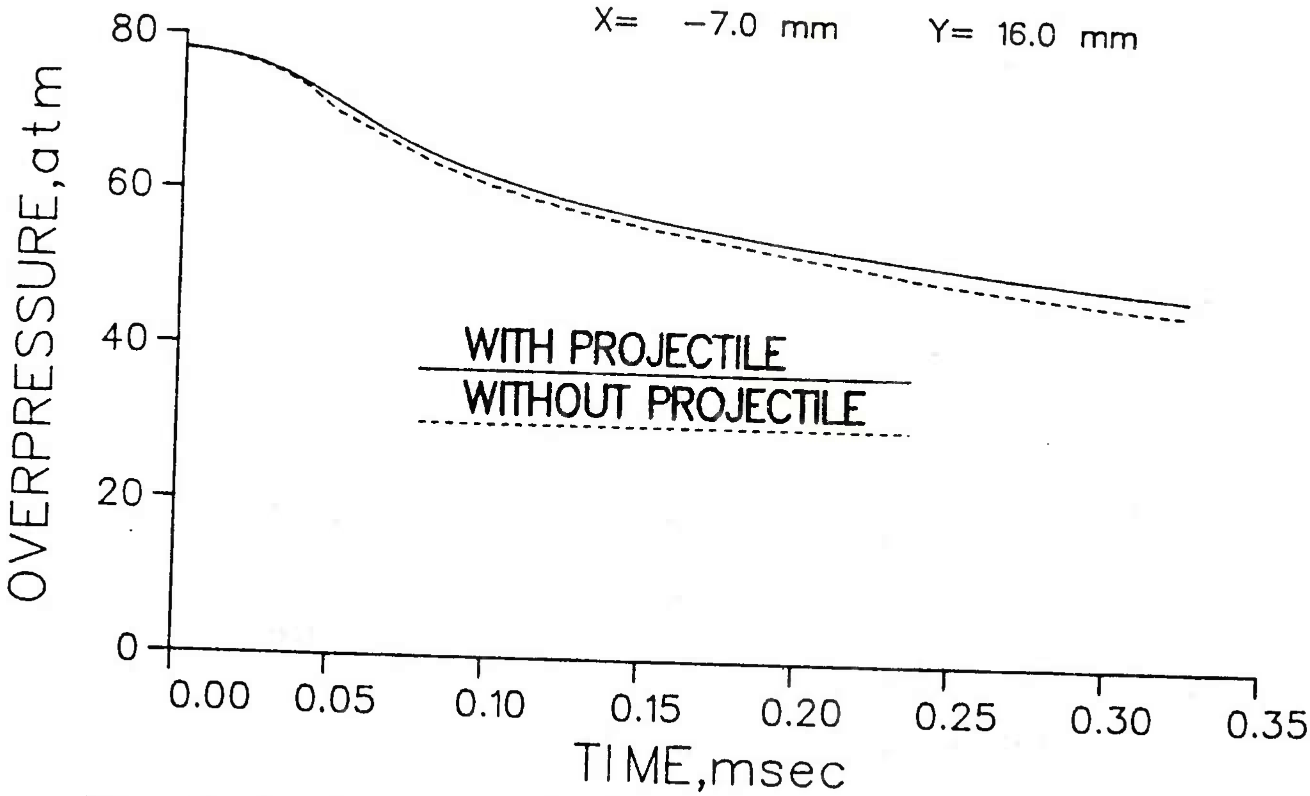

Figure 6. Comparison of In-Bore Pressures With and Without Projectile

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